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A COMPARISON OF SEVERAL AIRBORNE MEASURES OF TURBULENCE

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1. INTRODUCTION

The University of North Dakota has operated a Cessna Citation II research aircraft in support of the Federal Aviation Administration's efforts in developing the Next Generation Radar (NEXRAD) and Terminal Doppler Weather Radar (TDWR) weather radar systems. Flight missions were coordinated with the operations of ground-based Doppler radar systems to obtain simultaneous aircraft and radar observations of turbulence. These in situ and remote observations will be compared in order to help evaluate and improve the NEXRAD turbulence algorithm. This algorithm uses the Doppler spectrum variance to measure the strength of turbulent air motions; the "turbulence" felt in an aircraft is due to the response of the aircraft to these air motions. The ultimate goal of the algorithm is relate the Doppler velocity fluctuations to the aircraft response.

During these Citation flight missions, special attention was given to recording the levels of turbulence perceived by the air crew; however, these observations are not sufficient for a complete validation of the radar measurements. One shortcoming is that they are subjective. They are also typically not made at regular, frequent intervals, thus yielding an incomplete data record. Finally, they are valid only for the conditions relevant to that flight, such as aircraft type, weight and speed. Thus, to help overcome these inadequacies, a number of objective measures of turbulence have been selected for examination. These measures have been intercompared and related to the subjective observations for use in evaluating the turbulence algorithm.

2. DATA

The data used for this study were gathered as the Citation was operated during the spring and summer of 1989 in the Kansas City, Missouri area. These flights were conducted through and in the vicinity of convective clouds, primarily at altitudes below 6 km MSL. The aircraft was normally flown at true airspeeds of approximately 100 m s^{-1}.

The turbulence measures used in this study were derived from the output of a differential pressure transducer and a vertical accelerometer. The pressure transducer is mounted in the nose of the aircraft and connected to the dynamic and static pressure ports of a boom-mounted flow angle probe. The nominal 1/e response time of the transducer is 15 ms; however, damping of pressure fluctuations in the pitot line reduces the effective high frequency cutoff to approximately 8-10 Hz. The vertical accelerometer is integral to the inertial navigation system mounted near the center of gravity of the aircraft. Data signals are sampled at a rate of 24 Hz.

3. MEASURES OF TURBULENCE

Atmospheric turbulence produces fluctuations of the speed and direction of airflow past an aircraft in flight; as a result, the aircraft experiences momentary accelerations. The turbulence intensity may therefore be estimated by analyzing either the variations in airflow or the response of the aircraft.

Aircraft accelerations are physically sensed by the crew (and passengers) and may also necessitate control inputs to maintain desired aircraft flight attitude. The intensity scale established by the Federal Aviation Administration (FAA) is defined in terms of pilot sensory and motor reactions (FAA, 1985). The levels of intensity, ranging from negligible to potentially destructive, are Smooth, Light, Moderate, Severe and Extreme. These qualitative observations of turbulence were recorded periodically by the flight scientist.

A more direct and objective measurement of the aircraft response to turbulence may be made by an accelerometer. A change in airflow, or gust, will produce an incremental vertical load on the aircraft. The output of the Citation's vertical accelerometer was characterized in a number of different ways to find relationships between the vertical accelerations and other measures of turbulence (see Table 1, Numbers 3-7).

Variations in airflow occur as the aircraft encounters turbulent eddies in the atmosphere. The similarity theory of Kolmogorov states that within a certain range of eddy sizes, the inertial subrange, the transfer of energy from larger to smaller eddies can be described statistically by the eddy dissipation rate, ϵ. The inertial subrange does happen to include those eddies which are primarily significant to aviation (MacCready, 1964). Thus, a measure of ϵ provides a measure of turbulence.

The eddy dissipation rate can be calculated from measurements of the aircraft true airspeed V_t:

$$\epsilon_{va}{}^{1/3} = \left[\frac{D}{C}\right]^{1/2} \frac{1}{\delta x^{1/3}}$$

where D is a structure function of form

$$< (V_t(x) - V_t(x+\delta x))^2 >,$$

C is Kolmogorov's constant (1.77) and δx is the lag distance between samples. The lag distance used in this study was the distance travelled by the Citation in 0.5 s, or approximately 50 m. This scale should be well within the inertial subrange. The structure function was averaged over 10 s (approximately 1000 m) to yield values corresponding to the size of the radar sampling volume.

The $\epsilon^{1/3}$ derived from true airspeed data is a valuable estimator of atmospheric turbulence because it is a direct measure and is not dependent on aircraft parameters such as type, weight and speed. It is also incorporated into the NEXRAD turbulence algorithm where $\epsilon^{1/3}$ is calculated from the variance of the Doppler velocities (Bohne, 1985). Therefore, the values of $\epsilon^{1/3}$ derived from airborne observations should provide a means of verifying the algorithm which is more suitable than using aircraft response variables. (It should be noted, however, that significant sampling differences exist between the aircraft and radar observations.)

The eddy dissipation rate can also be estimated somewhat less directly from the vertical accelerometer output (Labitt, 1981):

$$\epsilon_{va}{}^{1/3} = \left[\frac{3\,D_{va}}{C}\right]^{1/2} \frac{m}{C_{L_\alpha} S \rho V_t \delta x^{1/3}}$$

where

D_{va} = acceleration structure function
m = mass of the aircraft
C_{L_α} = aircraft lift curve slope
S = wing area
ρ = air density at flight level.

It should be noted that in the computation of $\epsilon^{1/3}$ from the vertical accelerometer data, the aircraft parameters were treated as constant. One of these parameters, the mass of the aircraft, was clearly no constant, but varied with the fuel load. An average value of the mass has been assumed, but this could be in error by 10%, depending upon whether it was early or late in the flight. This error would then give a similar error to the computed $\epsilon^{1/3}$ values as the mass appears as a linear term in the formula.

Two other objective measures were derived from the airspeed measurements. These were simply the variance and standard deviation of the true airspeed.

Table 1. List of Derived Turbulence Parameters.

No.	Parameter
1	Turbulent kinetic energy dissipation rate to the 1/3 power derived from true airspeed.
2	Turbulent kinetic energy dissipation rate to the 1/3 power derived from vertical acceleration
3	Maximum value of the absolute value of the vertical acceleration during 1 second interval
4	Mean of the absolute value of the vertical acceleration during 1 second interval
5	Standard deviation of the vertical acceleration during 1 second interval
6	Maximum change in the vertical acceleration in 1/24th second
7	Variance of the 1/24th second changes in the vertical acceleration over one second
8	Variance in the true airspeed over 1 second interval
9	Standard deviation of the true airspeed over 1 second interval

4. COMPARISONS OF THE TURBULENCE MEASURES

4.1 Comparisons of Different Objective Measures

The values of $\epsilon^{1/3}$ as computed from the variations in true air speed have been compared to those values computed from the vertical accelerometer data. A scatter diagram of the respective values is shown in Fig. 1. The data upon which this figure is based were taken on three different flights when a fairly broad range of turbulence was experienced by the aircraft. In general, the agreement between the two computations was good. There was one exception, the results of which can be seen in the small clump of points located near the top of the diagram. This was caused by penetration of a strong updraft which resulted in strong vertical acceleration of the aircraft without an accompanying change in the true airspeed. The line plotted on the diagram represents perfect agreement between the two methods.

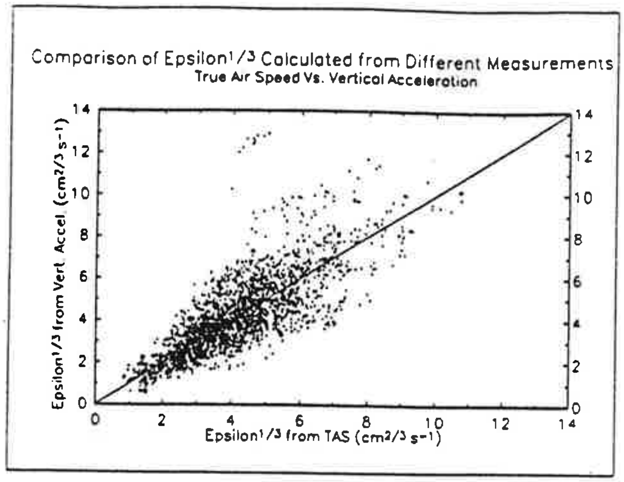

Fig. 1. Scatter diagram of $\epsilon^{1/3}$ computed from true airspeed as a function of $\epsilon^{1/3}$ computed from vertical accelerometer data.

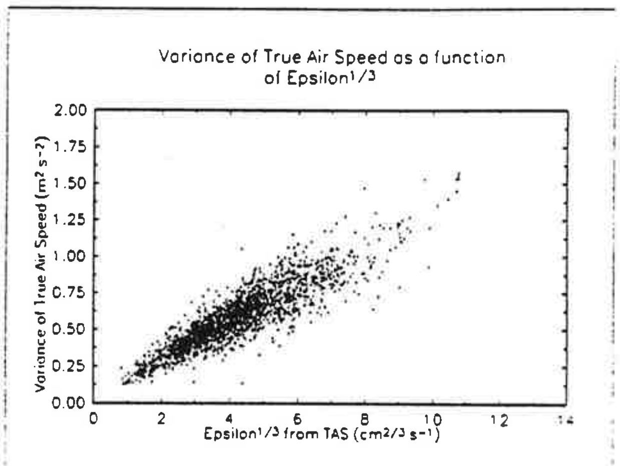

Fig. 2. Scatter diagram of the variance of true airspeed as a function of $\epsilon^{1/3}$ computed from true airspeed.

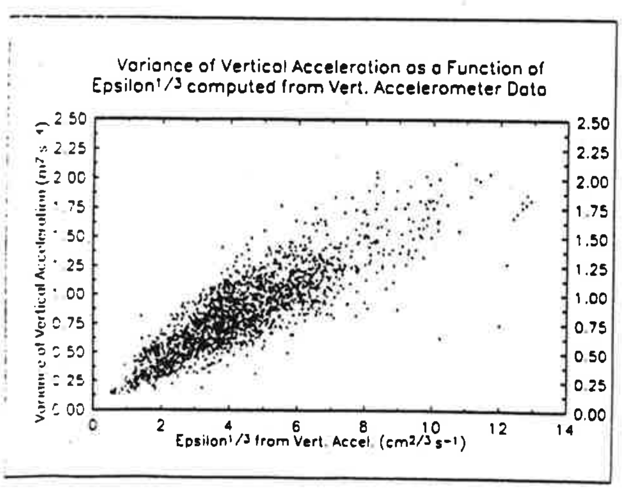

Fig. 3. Scatter diagram of the variance of vertical acceleration as a function of $\epsilon^{1/3}$ computed from true airspeed.

The values of $\epsilon^{1/3}$ were also compared to the other objectively-measured parameters described in Table 1. These parameters do not represent an exhaustive list of the possible parameters, but were chosen as candidates for the turbulence "felt" by the aircraft. Values of these other parameters were smoothed by a 10-second running mean for comparison with the values of $\epsilon^{1/3}$. Two of these are shown plotted in Figs. 2 and 3. Fig. 2 shows the variance of the true airspeed compared to the $\epsilon^{1/3}$ as computed from the true airspeed. The mutual dependence of these variables is obvious from the figure. Similarly, the variance of the vertical accelerometer compared to the $\epsilon^{1/3}$ values derived from the vertical accelerometer data (Fig. 3) shows a relatively strong relationship.

It is worthy of note that in both the figures discussed above, the independent measured variable is consistent; i.e., those variables dealing with true airspeed are together and those dealing with the vertical accelerometer data are together. As might be expected, a comparison of the variance of the true airspeed with the $\epsilon^{1/3}$ as derived from the vertical accelerometer data would show more scatter. Comparisons were made of many derived variables among which were those listed in Table 1. In general, the derived variables that could change sign, such as vertical acceleration or change in vertical acceleration, exhibited no significant correlation with any of the other variables. Those derived variables that did not change sign, such as the absolute value of the change in vertical acceleration or the variance of the vertical acceleration, tended to be highly correlated. The correlation matrix for the variables listed above as number 1 through 9 is shown in Table 2.

Table 2. Correlation matrix for objective measures of turbulence.

	Variable	1	2	3	4	5	6	7	8	9
1	"EPS"	1.00	0.79	0.70	0.66	0.70	0.56	0.53	0.79	0.83
2	"EPSVA"	0.79	1.00	0.81	0.77	0.81	0.54	0.51	0.65	0.71
3	"MAXABSG"	0.70	0.81	1.00	0.94	0.92	0.74	0.72	0.67	0.73
4	"AVABSG"	0.66	0.77	0.94	1.00	0.82	0.58	0.57	0.63	0.68
5	"SIGMAG"	0.70	0.81	0.92	0.82	1.00	0.79	0.75	0.70	0.76
6	"MAXDELG"	0.56	0.54	0.74	0.58	0.79	1.00	0.96	0.52	0.61
7	"VARDELG"	0.53	0.51	0.72	0.57	0.75	0.96	1.00	0.52	0.57
8	"VARTAS"	0.79	0.65	0.67	0.63	0.70	0.52	0.52	1.00	0.94
9	"SIGMATAS"	0.83	0.71	0.73	0.68	0.76	0.61	0.57	0.94	1.00

4.2 Comparisons of Subjective and Objective Measures

The comparisons between the subjective and objective measures were not done in the same statistical manner as the objective parameter intercomparisons. One reason for this is that the subjective reports were logged at relatively infrequent and irregular intervals. The reporting of turbulence intensity in any given flight segment also tends to be biased by the extreme accelerations which may or may not be representative of a continuous level of turbulence. It is, however, the strongest "bumps" which produce the most stress on the aircraft and its contents. Therefore, the subjective values were compared with the maximum or "peak" values of the objective measures. A subset of the five most promising objective parameters was chosen for study.

A time trace of the vertical accelerometer output was examined to identify flight segments where the turbulence was relatively homogeneous and where subjective estimates of its intensity had been recorded. A total of 74 data segments were selected from 11 flights. The segments ranged in length from approximately 30 s to 4 min (about 3-25 km); reported turbulence intensities ranged from Smooth to Severe. From within each segment, the peak values of the objective parameters were extracted and classified according to the subjective intensity associated with that segment.

Figures 4 and 5 show frequency distributions of two of the objective measures, the maximum absolute value of G and $\epsilon^{1/3}$. Despite the subjective nature of the crew reports there is good agreement between the measures. The transition points or threshold values of max G corresponding to increasing subjective intensities appear to be approximately 0.2g, 0.5g and 1.0g (Fig 4). These are identical to the World Meteorological Organization criteria. The threshold values of $\epsilon^{1/3}$ occur roughly at 2, 6 and 11 (Fig. 5). These transition points are not as sharp as for max G which is due in part to the fact that $\epsilon^{1/3}$ is a measure of turbulence, not aircraft response. Perhaps more significant is a possible contribution of pilot control inputs. Actions of the pilots to control the aircraft will likely have a greater effect on vertical accelerations than on airspeed measurements.

The threshold values for each of the five selected parameters are shown in Table 3. There is some uncertainty in fixing thresholds for severe turbulence because there are relatively few samples in the data set.

Table 3. Threshold values of objective parameters for subjective intensity levels.

	Light	Moderate	Severe
MAXABSG (G's)	0.2	0.5	1.0
SIGMAG (G's)	0.10	0.20	0.35
VARTAS (m^2 s^{-2})	0.5	2.0	5.5
EPS ($cm^{2/3}$ s^{-1})	2.5	6.0	10.5
EPSVA ($cm^{2/3}$ s^{-1})	2.0	6.0	10.0

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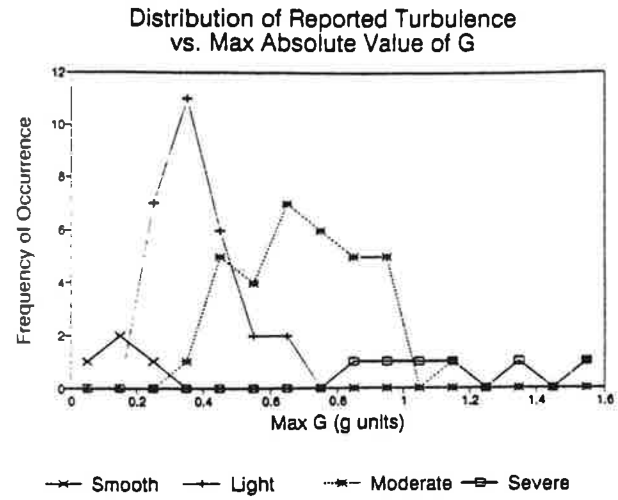

Fig. 4. Frequency distribution of subjective turbulence intensities as a function of the maximum absolute value of G.

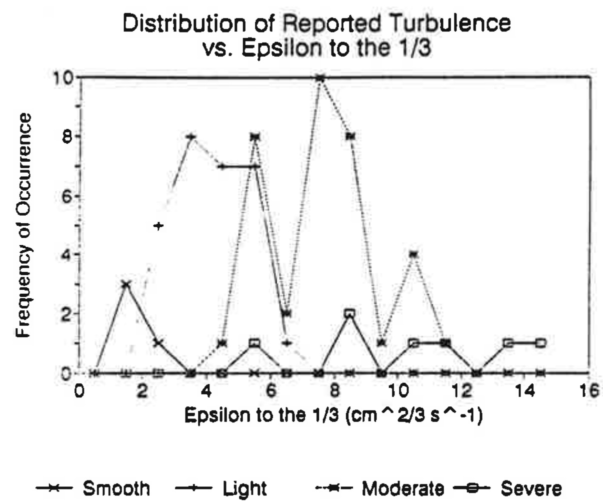

Fig. 5. Frequency distribution of subjective turbulence intensities as a function of $\epsilon^{1/3}$ computed from true airspeed.

REFERENCES

Bohne, A., 1985: Turbulence algorithm description. in Next Generation Weather Radar Algorithm Report, NEXRAD Joint System Program Office.

FAA, 1985: Aviation Weather Services. Federal Aviation Administration AC00-45C. U.S. Government Printing Office, Washington, D.C.

Labitt, M., 1981: Coordinated radar and aircraft observations of turbulence. Project Report ATC-108, Lincoln Laboratory, MIT.

MacCready, P.B., Jr. 1964: Standardization of gustiness values from aircraft. J. Appl. Meteor, 3, 439-449.